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Forearm temperature profile during the transient phase of thermal stress

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Summary. The transient temperature response of the resting human forearm immersed in water at temperatures (T_w) ranging from 15 to 36° C was investigated. Tissue temperature (T_t) was continuously monitored by a calibrated multicouple probe during the 3-h immersions. T_t was measured every 5 mm, from the longitudinal axis of the forearm to the skin surface. Skin temperature, rectal temperature, and blood flow ($\dot{Q}$) were also measured during the immersions. The maximum rate of change of the forearm mean tissue temperature ($\dot{T}_{t,max}$) occurred during the first 5 min of the immersion. $\dot{T}_{t,max}$ was linearly dependent on T_w ($P<0.001$), with mean values (SEM) ranging from −0.8 (0.1) °C·min^{-1} at 15° C to 0.2 (0.1) °C·min^{-1} at 36° C. The maximum rate of change of compartment mean temperature was dependent ($P<0.001$) on the radial distance from the longitudinal axis of the forearm. The half-time for thermal steady state of the forearm mean tissue temperature was linearly dependent on T_w between 30 and 36° C ($P<0.01$), with mean values (SEM) ranging from 15.6 (0.6) min at 30° C to 9.7 (1.2) min at 36° C and not different between 15 and 30° C, averaging 16.2 (0.6) min. There was a significant linear relationship between the half-time for thermal steady-state of the compartment mean temperature and the radial distance from the longitudinal axis of the forearm for each value of T_w tested ($P<0.001$). The data of the present study suggest that the forearm $\dot{Q}$ is an important determinant of the transient thermal response of the forearm tissue during thermal stress.

Key words: Cold stress – Cooling rate – Intramuscular temperature – Tissue temperature – Transient response

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Introduction

In a previous study (Ducharme et al. 1991), we considered the steady state temperature profile of the forearm tissue during immersion in water at temperatures (T_w) from 15 to 36° C. Although this is of valuable theoretical interest, practical, clinical or experimental situations usually deal with non-steady state of heat transfer since the thermal stress is not prolonged. This is the case, for example, during therapeutic application of heat and cold for treatment of athletic injuries.

Little research has been reported concerning the transient response of the limb tissue temperature (T_t) during thermal stress in humans. Although some authors have presented graphical descriptions of the limb T_t during the transient phase (Bazett and McGlone 1927; Bierman and Friedlander 1940; Barcroft and Edholm 1943, 1946; Brown et al. 1953; Clarke et al. 1958; Wolf and Basmajian 1973; McMaster et al. 1978; Johnson et al. 1979), these studies are restricted to one specific thermal exposure and/or one specific site inside the limb. Mitchell et al. (1970) developed an analytical model for the transient thermal response of human lower extremities, but the model can be applied only for cold stress. Lowdon and Moore (1975) presented a mathematical description of the upper arm T_t for one site inside the limb, but this was based only on the first 15 min of a cold stress. Aside from these studies, no mathematical description of the transient thermal response of the limb tissues is available for a broad range of temperatures.

The objective of the present study was to investigate the transient T_t profile of the resting human forearm immersed in water at T_w from 15 to 36° C. Equations were empirically derived from the experimental data to describe the transient response of the forearm tissue during the thermal stress. Such information would be useful for prediction modelling of thermoregulation and for application of thermal therapy.

Methods

A detailed description of the methods used has been presented in a previous paper reporting the forearm T_t at steady state during

Table 1. Mean anthropometric characteristics of the subjects; the anthropometric measurements were performed on both forearms and averaged for each subject

	Age (years)	Height (m)	Mass (kg)	A_D[a] (m^2)	Forearm[b] circumference (m)	Forearm[b] radius (mm)	Skin and fat[b] thickness (mm)	Muscle[b] thickness (mm)	Proportion by volume[b] Muscle (%)	Skin + Fat (%)	Bone (%)
Mean	23.2	1.79	76.9	1.95	0.28	41	3	38	78.2	13.7	8.2
SEM	1.9	0.02	3.6	0.04	0.01	1	0.4	1	2.0	2.0	0.5
Range	18–30	1.73–1.85	70.0–83.8	1.81–2.05	0.24–0.32	37–47	2–5	34–44	70.1–83.9	8.2–22.5	6.8–9.9

[a] Estimated total body surface area (m^2) of the subjects from the formula of Dubois and Dubois (1916)
[b] Measured approximately 90 mm from the olecranon process along the ulnar ridge of the forearm

thermal stress in water (Ducharme et al. 1991). The following is a brief description of the methods used in this study. The protocol was approved by Institutional Human Ethics Committees.

Anthropometric measurements. Table 1 lists the mean and range of anthropometric measurements of the 15 men used in this study. Anthropometry of the forearm was measured from computed tomography (CT) scans taken at the site of the muscle temperature measurements. The various characteristics were calculated from a photograph of the CT scans using computerized planimetry (graphic tablet model HP 9111A, computer model HP-85, Hewlett-Packard).

Temperature measurements. T_t was continuously monitored during the immersion every 5 mm from the longitudinal axis of the forearm (determined by CT scan) to the skin surface on the bulkiest part of the forearm, approximately 90 mm distal from the olecranon process along the ulnar ridge. Temperatures were recorded with a fine calibrated multicouple probe (Ducharme and Frim 1988) implanted under local anaesthesia (skin refrigerant, ethyl chloride, Graham-Field, New York, USA) by using the method described by Ducharme and Frim (1988). The position of the probe (and thus of each junction in the multicouple probe) in the forearm tissue was accurately known within 0.5 mm and remained stationary during the experiments. The forearm T_t values were corrected for the thermal conductivity effect along the wires of the probe (Ducharme and Frim 1988). The mean T_t ($\overline{T}_t$) of the forearm was calculated as follows:

$$\overline{T}_t = \sum_{i=1}^{i=n} \frac{V_i \cdot \overline{T}_i}{V_f} \quad (1)$$

where n is the number of 5-mm-thick concentric compartments in the forearm (from the axis to the skin) whose boundaries are defined by the junctions of the multicouple, V_i is the volume of compartment i, V_f is the volume of the forearm, and $\overline{T}_i$ is the mean temperature of the compartment i calculated by integrating the bioheat equation (Eq. 6 in Pennes 1948) between the points of temperature measurement and assuming uniform heat production within each compartment (see Appendix). The region of the forearm where the multicouple probe was implanted is assumed to be cylindrically symmetrical. Consequently, the ratio of volumes of an annular concentric compartment i to the total volume of all compartments is given by $(r_i^2 - r_{i-1}^2)/r_{sk}^2$ where r is the radius and sk refers to the skin surface. In this way, we are not inferring that the whole forearm is cylindrical, only that the region of interest, which may be a narrow wedge, has cylindrical symmetry. A schematic of this model is shown in Tikuisis and Ducharme (1991).

Skin temperature (T_{sk}) was measured a few millimeters away from the site of the implanted probe with a calibrated 40 gauge type T thermocouple. Rectal temperature (T_{re}) was measured using a calibrated thermistor probe inserted 150 mm beyond the anus. All temperature data were recorded continuously during the experiments using a computer-controlled data acquisition system (model HP-3052A, computer model HP-85, Hewlett-Packard). Mean values over 1-min periods were calculated for all measured variables.

Rate of change of T_t. The time rate of change of the mean forearm T_t ($\dot{T}_t$) was calculated for each 5-min period during the 3-h immersions as follows:

$$\dot{T}_t = (\overline{T}_{t(j)} - \overline{T}_{t(j-1)})/5 \quad (2)$$

where $\overline{T}_{t(j)}$ is the mean forearm tissue temperature at the end of the jth 5-min period, and $\overline{T}_{t(j-1)}$ is the $\overline{T}_t$ at the end of the previous 5-min period. T_i for each 5-mm thick compartment inside the forearm $\dot{T}_i$ was similarly calculated. The maximum value of $\dot{T}_t$ and $\dot{T}_i$ calculated during the 3-h immersion was chosen to represent $\dot{T}_{t,max}$ and $\dot{T}_{i,max}$, respectively, for that particular immersion.

Blood flow measurements. The forearm blood flow ($\dot{Q}$) was measured by the plethysmograph Whitney gauge technique (1953) using a mercury-in-Silastic circumference gauge (Parks Electronics Laboratory, Aloha, Ore., USA). The gauge was calibrated before each experiment using a previously described method (Ducharme et al. 1991).

Experimental procedure. Subjects reported to the laboratory at noon, on two separate occasions within a 2-week period. Following the muscle implantation of the multicouple probe, the subject, lightly dressed (T-shirt and casual pants), rested in a supine position under thermo-neutral conditions [air temperature (T_a) of 25.2 (1.1) °C, relative humidity of 40 (2)%] for 1 h. During that period, T_t, T_{sk}, and T_{re} were recorded continuously, the first measurement being taken approximately 10 min after the implantation of the probe. At the end of the resting period, the first series of measurements of $\dot{Q}$ was performed with the subject sitting comfortably and resting the forearm on a surface at the level of the heart. The subject then immersed his forearm and hand for 3 h in a well-stirred water bath maintained at T_w of either 15, 20, 30, 33 or 36° C (Haake F3 circulator temperature controller, Haake EK 51-1 immersion cooler, Haake E 52 circulator heater, Saddle Brook, N. J., USA). At the end of the 3-h immersion, a second series of measurements of $\dot{Q}$ was performed with the forearm still resting in the water bath. Each subject experienced two T_w chosen randomly, one for each forearm over a 2-week period. A total of 30 experiments were performed, 6 for each T_w.

Statistical analysis. The regression analysis, the tests of equality of lines (based on slope and intercept), and the independent t-tests were performed using the BMDP Statistical Program (Biomedical Computer Programs, BMDP, 1983, Los Angeles, Calif., USA). Only variables with significant coefficients ($P<0.05$) were included in the multiple regression equation (see Eq. 5). Equation 5 is the mean of five multiple regression analyses using randomly chosen independent data one value of the half-time of the compartment mean temperature ($\overline{T}_{i1/2}$) per experiment at a randomly chosen value of r for each analysis. The tests of equality of lines for the different relationships between the $\dot{T}_{i,max}$ and the ratio r/r_{sk} (see Fig. 6) were performed on linearized regressions using the natural logarithmic values of $\dot{T}_{i,max}$. Significant improvement at the 0.05 level of model parameters in the prediction of T_t using non-linear regression (see Eq. 6) was tested using the F-test (Drag-

er and Smith 1966). Where applicable, data are presented as means (SEM).

Results

No shivering activity was observed during any of the forearm immersions. T_{re} increased during the 3-h immersion period by 0.25 (0.03) °C ($P<0.001$; no significant difference among temperature conditions), probably due to the circadian cycle and/or to the tissue vasoconstriction in the extremities caused by the local cold stress.

Rate of change of forearm $\bar{T}_t$

Figure 1 shows the temporal evolution of the forearm $\bar{T}_t$ for each value of T_w tested. The rate of change in $\bar{T}_t$ was dependent on T_w, and was generally maximal during the first 5 min of immersion for all T_w tested. $\dot{T}_{t,max}$ was linearly dependent on T_w (correlation coefficient of 0.97; $P<0.001$) increasing from -0.79 (0.05) °C·min^{-1} at 15° C to 0.20 (0.07) °C·min^{-1} at 36° C (Fig. 2).

Figure 3 shows a linear relationship between the normalized forearm $\dot{T}_{t,max}$, and the forearm $\dot{Q}$ measured at thermal steady state, i.e. after 3 h of immersion (correlation coefficient of 0.65; $P<0.01$). The normalized maximum rate of change of $\bar{T}_t$ was obtained by dividing $\dot{T}_{t,max}$ by the difference between the forearm $\bar{T}_t$ before immersion ($\bar{T}_{t(0)}$) and T_w. This normalization gives a value that is inversely related to $\dot{T}_{t1/2}$. These normalized values were minimal (mean value of 0.04 (0.01) °C·min^{-1}·°C^{-1}) and not statistically different for $T_w \leq 30$° C when $\dot{Q}$ was minimal (<1.5 ml·min^{-1}·100 ml tissue^{-1}), but increased linearly and significantly with T_w up to 0.09 (0.01) °C·min^{-1}·°C^{-1} for values of $\dot{Q}$ up to 6.2 (0.5) ml·min^{-1}·100 ml tissue^{-1}. Note that in air at 25° C, $\dot{Q}$ was 3.55 (0.20) ml·min^{-1}·100 ml tissue^{-1}. Data for $\dot{Q}$ for this series of experiments were presented in a previous report dealing with the T_t of the forearm at thermal steady state (Ducharme et al. 1991).

Another way of describing the temporal evolution of the forearm $\bar{T}_t$ is to determine the half-time of its evolution to steady state ($T_{t1/2}$). These values were determined by fitting the profiles shown in Fig. 1 to exponential functions that asymptotically approached the steady state values measured after 3 h of immersion. In this way, the data from the entire immersion period were used. Alternatively, $T_{t1/2}$ can be determined by its reciprocal relationship to $\dot{T}_{t,max}/(\bar{T}_{t(0)}-T_w)$, but this would utilize only the initial period of the immersion. From

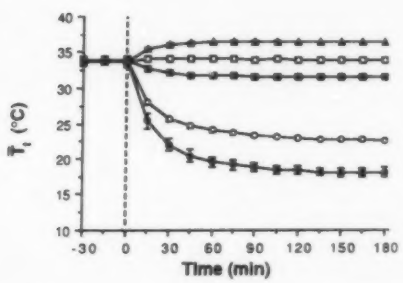

Fig. 1. Temporal evolution of the forearm mean tissue temperature ($\bar{T}_t$) for different water temperatures (T_w) tested. Data are expressed as means (SEM). For each data point, $n=6$. —●—, $T_w=15$° C; —○—, $T_w=20$° C; —■—, $T_w=30$° C; —□—, $T_w=33$° C; —▲—, $T_w=36$° C

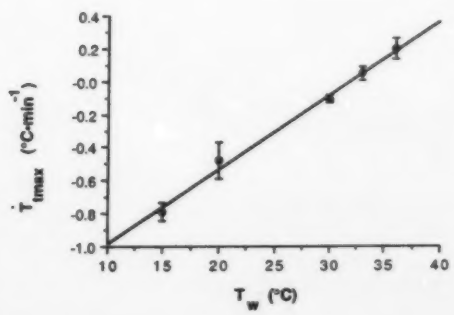

Fig. 2. Maximum rate of change of the forearm mean tissue temperature ($\dot{T}_{t,max}$) for each water temperature (T_w) tested. Data are expressed as means (SEM). For each value of T_w, $n=6$

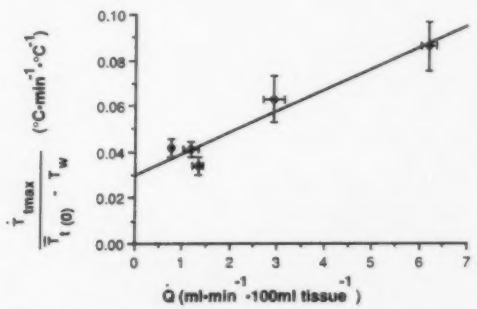

Fig. 3. Normalized maximum rate of change of the forearm mean tissue temperature ($\dot{T}_{t,max}/(\bar{T}_{t(0)}-T_w)$ as a function of the forearm blood flow ($\dot{Q}$) measured at thermal steady-state. Data are expressed as means (SEM). For each data point, $n=6$. See text for explanation of symbols

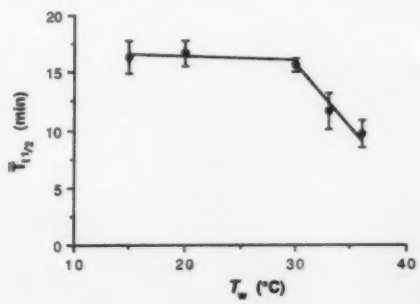

Fig. 4. Half-time for thermal steady-state of the forearm mean tissue temperature ($\bar{T}_{t1/2}$) for each water temperature (T_w) tested. Data are expressed as means (SEM); $n=6$ for each thermal condition

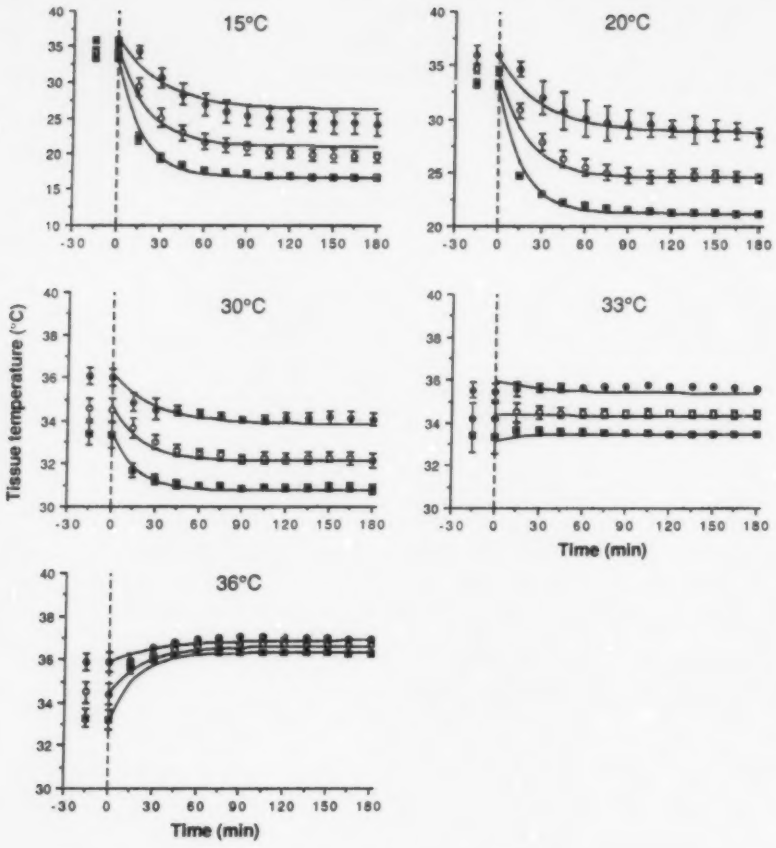

Fig. 5. Temporal evolution of the tissue temperature of the forearm for each water temperature tested. The tissue temperatures are represented for different values of r/r_{sk} (relative depth inside the forearm), where r is the radial distance from the longitudinal axis of the forearm, and r_{sk} is the forearm radius. Predicted values (—) calculated from Eq. 6 are also presented. Data are expressed as means (SEM). For each data point, $n = 6$. Values of r/r_{sk}: ● = 0.0 (axis); ○ = 0.5; ■ = 0.9

Fig. 3, it is evident that no change in $T_{t1/2}$ should occur in the T_w range 15–30° C since this is where $\dot{Q}$ did not change significantly. A linear change in $T_{t1/2}$, however, is expected in the T_w range 30–36° C. Therefore, regression of the data was performed separately for these two ranges of T_w. In the range 15–30° C, the mean $T_{t1/2}$ was 16.22 (0.60) min with no significant dependence on T_w (see Fig. 4). In the range 30–36° C, the following significant linear relationship was found:

$$T_{t1/2} = -0.99\,T_w + 45.13 \qquad (3)$$

$r = 0.78$, $P < 0.01$

Rate of change of compartment tissue temperature

Figure 5 presents, for each temperature tested, the temporal evolution of the forearm T_t for values of r/r_{sk} (relative distance from the longitudinal axis) representing the axial, intermediate, and superficial regions of the forearm. The rate of change of T_t during the first 5 min of immersion was maximum for the superficial tissues and decreased towards the longitudinal axis of the forearm. Thereafter, the rate of change in T_t decreased with immersion time for each r/r_{sk} value, and steady state was attained at all sites of the forearm within 3 h of immersion for all values of T_w ($\overline{T}_t$ changed by only 0.02 (0.01) °C in the last 10 min of immersion).

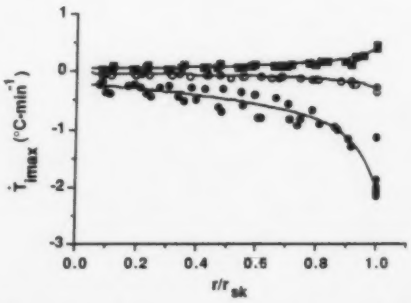

Fig. 6. Maximum rate of change of the compartment mean tissue temperature ($\dot{T}_{i,max}$) as a function of the relative distance from the axis of the forearm for water temperatures (T_w) of 15 (●), 30 (○) and 36 (■) °C. Predicted values (—) calculated from Eq. 4 are also presented

$\dot{T}_{i,max}$ was found to be dependent on the relative distance from the longitudinal axis under consideration (expressed by the ratio r/r_{sk}) as shown in Fig. 6. These maximal rates were greatest for values of r/r_{sk} approaching 1, which corresponds to the superficial layer of the forearm tissues. The relationships for the values of T_w tested were different from one another ($P < 0.05$).

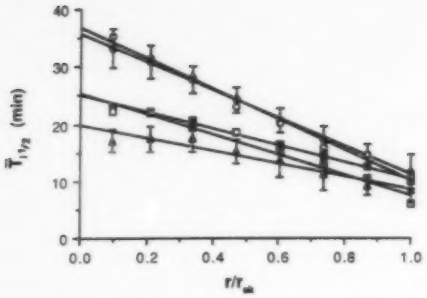

Fig. 7. Half-time for thermal steady state of the compartment mean tissue temperature ($\bar{T}_{i1/2}$) as a function of the relative distance from the longitudinal axis of the forearm (r/r_{sk}). Data are expressed as means (SEM). For each water temperature (T_w) tested, $n=6$. ●, $T_w=15°C$; ○, $T_w=20°C$; ■, $T_w=30°C$; □, $T_w=33°C$; ▲, $T_w=36°C$

The following empirical relationship between $\dot{T}_{i,max}$ and certain measured variables was found through non-linear regression for the whole range of T_w tested:

$$\dot{T}_{i,max}=(T_w-32.54)\cdot[0.06\cdot e^{-1.63(1-r/r_{sk})}+0.05\cdot e^{-14.41(1-r/r_{sk})}] \quad (4)$$

where $r<r_{sk}$ (i.e. the skin value is excluded). Figure 6 presents predicted values of $\dot{T}_{i,max}$ using Eq. 4, for different r/r_{sk} values, and for T_w of 15, 30, and 36° C.

Figure 7 depicts significant linear relationships between $\bar{T}_{i1/2}$ and the ratio r/r_{sk} for each temperature tested (correlation coefficient ranging from 0.70 to 0.85; $P<0.001$). These half-times were obtained in a similar fashion as before for the forearm $\bar{T}_t$ (see Fig. 4) but using the $\bar{T}_i$ in these cases. The slope of these relationships decreased linearly with T_w (correlation coefficient of 0.67; $P<0.001$), half-times ranging between 35.2 (5.2) min (at 20° C) and 17.1 (1.6) min (at 36° C) for r/r_{sk} of 0.1, but only between 11.6 (3.0) min (at 15° C) and 6.0 (2.1) min (at 33° C) for r/r_{sk} of 1.0. All relationships were different from one another ($P<0.05$) except between 15 and 20° C, and between 30 and 33° C.

Using the calculated values of $T_{i1/2}$ for different T_w and values of $r<r_{sk}$, the following empirical relationship was developed through a multiple regression to predict $T_{i1/2}$ for the whole range of T_w tested:

$$T_{i1/2}=20.76-0.41\,T_w-20.69\,r/r_{sk}+0.07\,\text{circ} \quad (5)$$

$$R=0.85,\ P<0.001$$

where circ is the circumference (in millimeters) of the forearm.

Using the measured temperatures at all points except at the skin and all times before and during the immersion, a final empirical relationship was developed through non-linear regression to predict the forearm T_t at any time during an immersion, as a function of the variables used in Eq. 5, and for the whole range of T_w tested (15–36° C):

$$\begin{aligned}T_t=&(16.68+0.57\,T_a-3.09\,r/r_{sk}+0.02\,\text{circ})\\&\cdot\exp[-t(-0.12+0.03\,r/r_{sk}\\&+44.14/\text{circ}-1.96\times10^{-4}\,T_w)]\\&+(18.65+0.51\,T_w-0.48(T_{re}-T_w)\cdot r/r_{sk})\\&\cdot(1-\exp[-t(-0.12+0.03\,r/r_{sk}+44.14/\\&\text{circ}-1.96\times10^{-4}\,T_w)]\end{aligned} \quad (6)$$

where T_a is the air temperature surrounding the forearm before the immersion (23–27° C), and t is the immersion time in minutes. The first and third lines of the Eq. 6 represent, respectively, the components corresponding to the forearm T_t at steady state in air before immersion, and in water at thermal steady state described in a previous study (Ducharme et al. 1991). The second and fourth lines represent the effect of the immersion time on the T_t of the forearm during the transient phase of the thermal stress. Figure 5 presents predicted values of forearm T_t using Eq. 6, for different r/r_{sk} values, and all T_w tested. Equation 6 can be used for the prediction of the forearm T_t at thermal steady state during air exposure (T_a ranging between 23 and 27° C), and for the prediction of the transient and steady state forearm T_t during water immersion (T_w ranging between 15 and 36° C).

In the Eqs. 4–6, the skin + fat thickness was not a significant parameter for the prediction of $\dot{T}_{i,max}$, $T_{i1/2}$ and T_t.

Discussion

Characteristics of the transient phase of the forearm T_t

To characterize the T_t of the forearm during the transient phase of different thermal stress in water, two parameters were focused on, namely the maximum rate of change of T_t, found during the first 5 min of the immersion, and $T_{t1/2}$. The data show that both parameters are dependent on the thermal stress imposed, that is, $\dot{T}_{t,max}$ and $\dot{T}_{i,max}$ increase (positive slope), while $T_{t1/2}$ and $T_{i1/2}$ decrease (negative slope) with increasing T_w. In addition, the parameters associated with $\dot{T}_{i,max}$ and $T_{i1/2}$ are also dependent on the distance from the axis of the forearm, the more superficial tissues being more affected by the T_w than the deeper tissues. It is possible that the forearm T_t responses to the different thermal stress may have been also subjected to circadian variations, although this effect is considered to be minimal for the time period involved (3 h).

These observations are in agreement with the results of previous studies which have shown that the rate of cooling is most rapid during the first few minutes of cold stress (Lowdon and Moore 1975), and that the time required to achieve thermal steady state for T_{sk} (Montgomery and Williams 1977), and for the subcutaneous and muscle temperatures (Barcroft and Edholm 1943; Brown et al. 1953) decreases with increasing environmental temperature. In addition, Brown et al. (1953) have shown that the time required for stabilization of T_t during a thermal stress increases with increasing depth inside the limb (the subcutaneous tissue stabilizes more rapidly than the muscle tissue).

The present results show that for the same thermal stress, there is an inter-individual variation of the forearm T_t, $T_{t1/2}$, and the rate of change of T_t. This variability is accounted for by variables other than the subcutaneous fat thickness such as the circumference of the forearm as expressed in Eqs. 5 and 6. These results are partially in agreement with those of Lowdon and Moore (1975), who showed that the rate of change of the muscle temperature during cold therapy was inversely proportional to both the skinfold thickness and to the arm circumference. The discrepancy regarding the effect of the subcutaneous fat thickness can be explained by the narrow range and small values of fat thickness present for our subjects (see Table 1).

Mitchell et al. (1970) assumed that the time to cool a leg to within 1% of steady state is a function of the diameter of the leg only. If this prediction is applied to a limb of 0.081 m diameter (average value of forearm diameter in this study), the calculated value is 2.05 h, which overpredicts by 13% the present experimental value of 1.82 h for the immersion at 15° C, and by 78% the present experimental value of 1.2 h for the immersion at 36° C. Thus, it would appear that the prediction by Mitchell et al. (1970) gives an acceptable estimation of the time required to attain steady state of the limb T_t only during cold stress when the limb $\dot{Q}$ is minimum. The time to achieve steady state is not only a function of the diameter of the limb, but also dependent on the temperature of the environment, as described by Eq. 5.

Relationship between $\dot{Q}$ and both $\dot{T}_{t,max}$ and $T_{t1/2}$

In a previous report (Ducharme et al. 1991), it has been suggested that the convective heat exchange between blood and tissue plays an important role on the forearm T_t at steady state during a thermal stress. The same role is expected during the transient phase of the thermal stress. As shown in Fig. 3, when $\dot{T}_{t,max}$ is normalized for the initial temperature difference between that of tissue and the environment, the normalized maximum rate of change of T_t shows a linear relationship with the forearm $\dot{Q}$ measured at thermal steady state. The forearm $\dot{Q}$ values used in this relationship are only an approximation of the forearm $\dot{Q}$ at 5 min of immersion since, according to Brown et al. (1953), the forearm $\dot{Q}$ stabilizes within 10 min after the onset of an immersion in water at T_w ranging between 10 and 35° C. When the $\dot{Q}$ value is extrapolated to zero, $\dot{T}_{t,max}/(\overline{T}_{t(0)} - T_w)$ represents the reciprocal of the time constant or the normalized rate of cooling of in vitro tissues. This rate of cooling follows exactly the cooling law of Newton (refer to Carslaw and Jaeger 1959), which stipulates that the heat transfer from the tissue to the environment is proportional to the temperature difference between the two media. The results of this study show that for a cold stress at $T_w \leq 30°$ C, the normalized maximum rates of change of T_t were similar, having a mean value of 0.04 (0.002) $°C \cdot min^{-1} \cdot °C^{-1}$, which is close to the value extrapolated for in vitro tissue (0.03 (0.001); see Fig. 3). One can therefore postulate that the rate of cooling of the forearm during cold stress at T_w between 15 and 30° C closely follows the cooling law of Newton. However, when the forearm $\dot{Q}$ increases over the minimal value during cold stress, which occurs for $T_w > 30°$ C, $\dot{Q}$ through the tissue becomes an important determinant of the rate of change of T_t.

The tissue $\dot{Q}$ increases the rate of change of T_t through the increase of the convective heat transfer with the tissue. It is therefore expected that $\dot{Q}$ also has an influence on the time required to achieved thermal steady-state of T_t during the thermal stress. The increase of the normalized maximum rate of change of the forearm T_t with $\dot{Q}$ shown in Fig. 3 for $T_w \geq 30°$ C can be explained by an increase of the effective thermal conductivity of the forearm tissue with the $\dot{Q}$ (Ducharme and Tikuisis 1991). If $\dot{Q}$ not change significantly during the immersion from its value at 5 min, then the half-time of the evolution of T_t to steady state can be determined through its reciprocal relationship to $\dot{T}_{t,max}/(\overline{T}_{t(0)} - T_w)$. To test this relationship, half-times were calculated from the mean values of $\dot{T}_{t,max}/(\overline{T}_{t(0)} - T_w)$ shown in Fig. 3. These were 18.2, 11.2, and 8.1 min for $T_w = 15$–30° C, 33, and 36° C. These values compare closely to the respective values of 16.2 (0.6), 11.6 (1.4), and 9.7 (1.2) min shown in Fig. 4. Hence, the assumption that $\dot{Q}$ does not change appreciably during the immersion from its value at 5 min is supported.

In conclusion, this study demonstrated that during the transient phase of a thermal stress in water, the forearm T_t, and $T_{t1/2}$ are dependent on the thermal stress imposed, the distance from the axis of the forearm, and the arm circumference of the subject. In addition, the data of the present study suggest that the forearm $\dot{Q}$ is an important determinant of the transient thermal response of the forearm tissue during thermal stress.

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References

Barcroft H, Edholm OG (1943) The effect of temperature on blood flow and deep temperature in the human forearm. J Physiol 102:5–20

Barcroft H, Edholm OG (1946) Temperature and blood flow in the human forearm. J Physiol 104:366–376

Bazett HC, McGlone B (1927) Temperature gradients in the tissues in man. Am J Physiol 82:415–451

Bierman W, Friedlander M (1940) The penetrative effect of cold. Arch Phys Med Rehabil 21:585–592

Brown GM, Hatcher JD, Page J (1953) Temperature and blood flow in the forearm of the Eskimo. J Appl Physiol 5:410–420

Carlslaw HS, Jaeger JC (1959) Conduction of heat in solids, 2nd edn. Clarendon, Oxford

Clarke RSJ, Hellon RF, Lind AR (1958) Vascular reactions of the human forearm to cold. Clin Sci 17:165–179

Drager WR, Smith H (1966) Applied regression analysis. Wiley, New York

Dubois D, Dubois EF (1916) A formula to estimate the approximate surface area if height and weight be known. Arch Intern Med 17:863–871

Du harme MB, Frim J (1988) A multicouple probe for temperature gradient measurements in biological materials. J Appl Physiol 65:2337–2342

Ducharme MB, Tikuisis P (1991) In vivo thermal conductivity of the human forearm tissues. J Appl Physiol 70:2682–2690

Ducharme MB, VanHelder WP, Radomski MW (1991) Tissue temperature profile in the human forearm during thermal stress at thermal stability. J Appl Physiol 71:1973–1978

Johnson DJ, Moore S, Moore J, Oliver RA (1979) Effect of cold submersion on intramuscular temperature of the gastrocnemius muscle. Phys Ther 59:1238–1242

Lowdon J, Moore RJ (1975) Determinants and nature of intramuscular temperature changes during cold therapy. Am J Phys Med Rehabil 54:223–233

McMaster WC, Liddle S, Waugh TR (1978) Laboratory evaluation of various cold therapy modalities. Am J Sports Med 6:291–294

Mitchell JW, Galvez TL, Hengle J, Myers GE, Siebecker KL (1970) Thermal response of human legs during cooling. J Appl Physiol 29:859–865

Montgomery LD, Williams BA (1977) Variation of forearm, hand, and finger flow indices with ambient temperature. Aviat Space Environ Med 48:231–235

Pennes HP (1948) Analysis of tissue and arterial blood temperatures in the resting human forearm. J Appl Physiol 1:93–122

Tikuisis P, Ducharme MB (1991) Finite-element solution of thermal conductivity of muscle during cold water immersion. J Appl Physiol 70:2673–2681

Whitney RJ (1953) The measurement of volume changes in human limbs. J Physiol (Lond) 121:1–27

Wolf SL, Basmajian JV (1973) Intramuscular temperature changes deep to localized cutaneous cold stimulation. Phys Ther 53:1284–1288

Appendix

Derivation of $\bar{T}_i$. Assuming uniform heat production and cylindrical geometry, the solution of the bioheat equation (Eq. 6 in Pennes 1948) is given by

$$T(r) = T_0 - (T_0 - T_1)(r/r_1)^2 \tag{A1}$$

for the core compartment (i.e. $0 \le r \le r_1$) where T_0 and T_1 are the temperatures at $r = 0$ and $r = r_1$, respectively, and where r is the radical distance from the longitudinal axis of the forearm. For the concentric annular compartments (i.e. for $i \ge 2$), the solution is given by

$$T(r) = T_{i-1} - A(r^2 - r_{i-1}^2) + B\ln(r/r_{i-1}) \tag{A2}$$

where

$$A = q_v/4k \tag{A3}$$

$$B = \frac{(T_i - T_{i-1}) + A(r_i^2 - r_{i-1}^2)}{\ln(r_i/r_{i-1})} \tag{A4}$$

and q_v is the volumetric heat production and k is the thermal conductivity.

$\bar{T}_i$ is found by integration as follows:

$$\bar{T}_i = \int_{r=r_{i-1}}^{r=r_i} T(r)r\,dr \Big/ \int_{r=r_{i-1}}^{r=r_i} r\,dr \tag{A5}$$

which has the solution

$$T_1 = (T_0 + T_1)/2 \tag{A6}$$

for the core compartment (i.e. $i = 1$) and

$$\bar{T}_i = T_{i-1} - \frac{A(r_i^2 - r_{i-1}^2)}{2} + B\left[\frac{\ln(r_i/r_{i-1})}{1 - r_{i-1}^2/r_i^2} - \frac{1}{2}\right] \tag{A7}$$

for the annular compartments (i.e. $i \ge 2$)